International Journal of Learning, Teaching and Educational Research
Vol. 24, No. 2, pp. 322-351, February 2025
https://doi.org/10.26803/ijlter.24.2.17
Received Oct 11, 2024; Revised Jan 28, 2025; Accepted Feb 28, 2025

Empowering Future Innovators: A TRIZ-Integrated Design Thinking Approach to Engineering Prototyping and Entrepreneurship in Oman

Prekerthi Panikar
College of Engineering
National University of Science and Technology, Muscat, Oman

Colin Milligan
Department of Academic Development & Student Learning
Glasgow Caledonian University, UK

Ahmed Hassan Al Bulushi, Syed Mohammad Rizwan
College of Engineering
National University of Science and Technology, Muscat, Oman

Nabila Al Balushi
Department of Mathematics and Statistics
University of Technology and Applied Sciences, Muscat, Oman

Abstract. The onset of the Fourth Industrial Revolution (4IR) introduced advanced technologies that engineering specialists could use to their benefit. This study sets out to explore if the engineering curriculum, as well as the engineering pedagogy, has had a chance for a facelift. Integrating technologies in design-thinking is seen as enhancing graduates' skills in effectively incorporating technologies into engineering innovations. A survey data involving 200 third and fourth-year engineering graduates at the College of Engineering (CoE), National University of Science & Technology (NUST), Oman, were analyzed using Structural Equation Modeling (SEM) to study the relationship between students' self-perception of Integrated Design Thinking, Innovation Capabilities, Systematic Invention, and self-reported familiarity and the Knowledge of Engineering Innovation Tools, and self-confidence in Prototyping. The findings reflect a positive relationship between the observed variable and Prototyping, thus consolidating the necessity for an educational framework integrating TRIZ, design thinking, and technology through pedagogy and assessments. In this way, universities can guarantee that graduates cultivate innovation capabilities, entrepreneurial mindset and proficiency in rapid prototyping and solution enhancement. Introducing engineering students to design and innovation requires a targeted method that aligns with best practices and emerging technologies to apply them in real problem-solving. This study evaluates the critical role of human-centered design thinking, aligned with the technology-centered TRIZ, in honing the predictive design approach to prepare the engineers of tomorrow through a transformation in pedagogy and assessments. This study on TRIZ-Integrated Design Thinking is the first in Oman and is expected to contribute to broader research involving other disciplines and stakeholders.

Keywords: Integrated Design-Thinking; Engineering Entrepreneurship; Oman; Innovation Capability; Theory of Inventive Problem Solving-TRIZ

1. Introduction

Design thinking (DT) is an essential skill for engineers as it enhances problem-solving abilities, promotes innovation, and advances user-centered design. Creativity and innovation are crucial components of engineering and engineering education. Indeed, they contribute significantly to a product's uniqueness and effectiveness as a solution to a problem. However, the relationship between engineering, innovation, and creativity often appears disconnected. Cropley (2015) warns that we risk producing fewer entrepreneurial and innovative engineers unless this disconnect is resolved in engineering education.

Omani higher education institutions continually endeavor to elevate standards in STEM (science, technology, engineering, and mathematics) education. There is a growing need to reevaluate the engineering curricula to assess their fitness for purpose and alignment with Oman's national priorities and UN Sustainable Development Goals (UNSDGs). Implementing creative methodologies that promote a transition to design thinking is essential. Engineering students require diverse organizational, interpersonal, and technical competencies to enhance their entrepreneurial endeavors. The design thinking methodology requires incorporating emerging technologies and a cohesive pedagogical framework to strengthen invention and innovation skills. This study advocates implementing emerging technologies and TRIZ-Integrated Design Thinking approach at CoE, NUST, and Oman to cultivate innovation and entrepreneurial capabilities among engineering students.

1.1 The Study Objectives

The objectives of this paper are as follows:

1. To review the literature to determine the importance of TRIZ-integrated Design Thinking (DT) for engineering graduates.
2. To statistically analyse the relationships between CoE students' self-perception of Integrated Design Thinking, Innovation Capabilities, Systematic Invention, self-reported familiarity with the Knowledge of Engineering Innovation Tools, and self-confidence in Prototyping.
3. To propose a framework integrating DT, engineering technologies, and TRIZ in the engineering curriculum to encourage innovations.

1.2 The Research Question:
The research question addressed in this paper is :

How can the TRIZ-Integrated Design Thinking strategy enhance graduate engineers' self-perceived innovation capabilities?

1.3 Paper Organization
Section 1 presents an introduction to DT, before elucidating the emerging need for awareness of the DT process and explaining the objectives of this study. Next, the literature review on DT and the contributing factors to develop a conceptual model are presented in Section 2. The research methodology, research design, and demographic composition are discussed in Section 3. The findings are revealed in Section 4 and Section 5 presents the discussion, limitations of the study and recommendations for future research. Finally, the paper is concluded in Section 6.

As indicated above, Section 2 presents a literature review, highlighting the relationship between DT and the factors contributing to capacity building for innovation among engineering graduates.

2. Literature Review
2.1 Theoretical Underpinnings in Education 4.0 and Industry 5.0
Contemporary shifts in educational paradigms, exemplified by Education 4.0, emphasize student-centered and technology-driven learning environments. Miranda et al. (2021) identified core components of Education 4.0 in engineering education, underlining the need for adaptive, technology-enabled frameworks that promote creativity and innovation. Similarly, Broo et al. (2022) discussed the evolving requirements of engineering education in the context of Industry 5.0, in which human-centric approaches and sophisticated technological tools are paramount. Integrating TRIZ within these modern educational frameworks allows bridging theoretical knowledge with practical, hands-on problem-solving, thereby enhancing students' invention self-efficacy.

The Human Capital Theory drives this study and highlights how the specialized technical and problem-solving skills acquired through an engineering education can be strategically combined with engineering entrepreneurial competencies. Dynamic curriculum and teaching strategies is the call in the fast-paced, technologically led engineering program to equip graduates with the expertise and confidence to navigate the complexities of innovation and /or start an engineering venture.

2.2 Design Thinking and Engineering Invention and Innovation
Encouraging a human-centered approach to solving complex, real-world problems, design thinking has become a cornerstone of modern engineering entrepreneurship education. Rather than merely teaching technical skills, educators now emphasize understanding user needs, fostering creativity, and promoting innovation through empathetic engagement, iterative prototyping, and active collaboration (Razzouk & Shute, 2012; Beckman & Barry, 2007; Dell'Era et al., 2025). This holistic perspective recognizes that successful engineering solutions emerge from thoughtful problem-framing, whereby engineers step

back, explore the context, and incorporate various viewpoints before devising technical strategies (Eisenbart et al., 2022).

Integrating design thinking into project-based learning, students engage in hands-on, constructive activities that sharpen their empathy, creativity, and collaborative abilities (Jiang & Pang, 2023; Guaman-Quintanilla et al., 2003). Researchers highlight that these attributes are vital for tackling the fast-paced technological landscape, enabling engineers to address ambiguity and adapt to evolving market demands (Habbal et al., 2024). Design thinking also aligns with socio-constructivist teaching philosophies, encouraging active learner participation and reflection (Bharathi & Pande, 2024; Pande & Bharathi, 2020; Zappe et al., 2013). As educators reevaluate pedagogical approaches to emphasize invention and innovation, design thinking is key (Tidd, 2023). Its human-centered, iterative framework equips future engineers with the mindset and practical skillset needed for successful entrepreneurship and impactful engineering practice (Meyer et al., 2020; Liedtka, 2018).

Section 2.3 reviews the literature on the significance of enhancing innovation capabilities among engineering students.

2.3 Innovation Capability

Innovation capability (IC) is increasingly recognized as vital in engineering education. As Jørgensen and Busk (2007) explain, it involves generating and implementing fresh solutions that enhance the value of an organization or product. Expanding on this, Dumas et al. (2016) emphasize the importance of identifying opportunities, using resources effectively, and translating ideas into meaningful advancements. In essence, innovation capability calls for innovative problem-solving, knowledge integration, and execution skills—all underpinned by value creation.

Recent research advocates embedding these qualities into engineering curricula. Ovbiagbonhia et al. (2023) and Mendoza-Silva (2021) note that many traditional teaching methods do not adequately prepare students for the rapidly changing demands of modern engineering. Consequently, educators are urged to shift toward project-based learning, real-world problem-solving, and industry collaboration (Genco et al., 2012; Charosky et al., 2022). Such approaches help to foster creativity, critical thinking, and an ability to work across disciplinary boundaries—skills that are fundamental to innovation (Dym et al., 2005).
Beyond curriculum design, studies have also highlighted the role of institutional culture and collaboration. For instance, Selznick and Mayhew (2018) argue that committed leadership and a supportive academic environment are essential for nurturing risk-taking and experimentation. Similarly, Jamieson and Shaw (2020) emphasize that strong networks and strategic partnerships can encourage innovative thinking among faculty and students. Historical insights also show that adapting educational techniques and building external relationships have consistently driven innovation in engineering programs (Saunila & Ukko, 2012).
Collectively, these findings underline the need for an ecosystem that supports innovative mindsets, from classroom experiences to broader organizational

backing. Design thinking, problem-based learning, interdisciplinary activities, entrepreneurial education, and technology integration can powerfully equip future engineers to tackle global challenges and drive economic growth.

Drawing from this review, we propose the following hypotheses:

H1: Self-perception of Innovation Capabilities positively influence the development of Self-perception of Integrated Design Thinking.

H2: Self-perception of Innovation Capabilities positively influences self-reported confidence in Prototyping.

Section 2.4 reviews embedding Systematic Inventive Thinking processes with Integrated Design Thinking.

2.4 Systematic Inventive Thinking with TRIZ

As Barak and Goffer (2002) explained, Systematic Invention is a methodical, reproducible process that enhances creativity by directing innovators through problem identification, research, ideation, prototype, and iterative feedback. This systematic methodology reduces dependence on impromptu creativity and prioritizes standardized techniques for attaining uniform outcomes. Despite their close relationship, Systematic Invention Thinking and Structured Innovation have different purviews. The former emphasizes the iterative creation of new concepts, whereas the latter oversees the entire innovation lifecycle, coordinating objectives, assessing ideas, and commercializing results (Lichtenthaler, 2020).

The use of TRIZ has become increasingly popular in educational settings to foster creativity and innovation skills. Focusing on finding and resolving contradictions using tools such as the Contradiction Matrix and the 40 Invention Principles (Chou, 2021), TRIZ has demonstrated improved problem-solving skills and creativity amongst students (Park, 2023; Livotov, 2015; Chang et al., 2016). Mohammadi et al. (2024) observe that training students to recognize and resolve system conflicts encourages higher creativity, while Li and Ren (2024) emphasize that TRIZ-based approaches maximize innovation and entrepreneurial courses. To enhance creative processes and guarantee user relevance, TRIZ can be integrated with design thinking, prioritising human-centered problem-solving via empathizing, defining, ideating, prototyping, and testing (Chang et al., 2023; Tavanti, 2023). By complementing iterative prototyping (Petrakis et al., 2021), reflective practice (Bender-Salazar, 2023; Ericson, 2022), and cross-disciplinary collaboration (Wu, Z., 2022). Zlotin & Zusman (2020) have come up with TRIZ software for creativity and Innovation support. Collectively, these frameworks are aimed at enhancing the efficacy of human-centered innovation processes and results.

Based on the above review, we propose the following hypotheses:

H6: Self-reported application of Systematic Invention significantly influences Self-perception of Integrated Design Thinking.

H7: Self-reported application of Systematic Invention positively influences self-reported confidence in Prototyping.

Section 2.5 reviews the literature on integrating engineering technologies with TRIZ-based design thinking.

2.5 Integration of Technologies and TRIZ-based DT in Engineering Innovation
Recent research has demonstrated a growing interest in combining TRIZ, a methodical innovation framework developed by Soviet engineer Genrich Altshuller in the 1940s, with Design Thinking, a user-centered approach that emphasizes empathy and creativity (Petrov, 2019; Chasanidou et al., 2015). TRIZ is mainly focused on addressing engineering challenges by identifying contradictions and resolving them with tools such as the Contradiction Matrix and 40 Inventive Principles. On the other hand, Design Thinking centers on understanding the human aspect of a problem (Nguyen et al., 2022). Combining these two approaches can provide complementary benefits, with TRIZ offering effective technical solutions while Design Thinking ensures that these solutions remain user-friendly and socially relevant (Da Silva et al., 2020).

Studies indicate that incorporating TRIZ into engineering curricula enhances students' problem-solving abilities and builds their confidence in tackling complex, open-ended challenges (Sheng, 2023; Cano-Moreno et al., 2021; Belski, 2019). This integration has proven successful in improving product and service design outcomes. For example, Chou (2021) illustrates that TRIZ can be incorporated into service design principles to create resilient and innovative products. Similarly, Sheng (2023) highlights how students become more adept at managing uncertainty and enhancing their inventive capabilities, crucial skills in today’s fast-changing landscape. Combining TRIZ’s systematic approach with Design Thinking’s focus on the human element can lead to groundbreaking innovations and reduced research and development timelines while ensuring that people remain at the core of the process (Savransky, 2000; García-Manilla, 2023; Weigert & de Carvalho, 2023).

TRIZ has evolved significantly, offering powerful tools for systematically addressing engineering and design contradictions (Spreafico, 2022). With the integration of advanced technologies such as virtual reality (VR), machine learning (ML), simulation modeling, additive manufacturing (AM), the Systematic Invention Process (SI), and axiomatic design, the potential of TRIZ is now expanding (Wang et al.,2022; Yin et al.,2015). Such advancements signal a transformative shift in terms of how we approach product ideation and development, promising faster and more creative results (Wang et al., 2022; Carvalho Botega & da Silva, 2022). Recent studies support this vision, with authors including Martorelli and Gloria (2023), Dodun et al. (2022), Qiu et al. (2022), and Mawale et al. (2016) emphasizing the potential of enhanced TRIZ in guiding the creation of next-generation products. In particular, Qiu et al. (2022) advocate for holistic design frameworks that combine Systematic Invention processes with emerging technologies such as simulation and VR, offering designers immersive environments to test and refine TRIZ-driven ideas more efficiently. This approach can help bridge the gap between conceptualization and real-world validation, paving the way for genuinely transformative product innovations.

Based on this review, we propose the following hypotheses:
H3: Self-perception of Integrated Design Thinking significantly influences self-reported confidence in Prototyping.

H4: Self-reported familiarity with Engineering Innovation Tools positively influences Self-Perception of Integrated Design Thinking.

H5: Self-reported familiarity with Engineering Innovation Tools positively influences self-reported confidence Prototyping.

H8: Self-perception of Integrated Design Thinking mediates the relationship between Self-perception of Innovation Capabilities and self-reported confidence in Prototyping.

H9: Self-perception of Integrated Design Thinking mediates the relationship between Self-reported familiarity with Engineering Innovation Tools and self-reported confidence in Prototyping.

H10: Self-perception of Integrated Design Thinking mediates the relationship between Self-reported application of Systematic Invention and self-reported confidence in Prototyping.

Section 2.6 reviews the literature on integrating engineering technologies with TRIZ-based Design Thinking for engineering students in Oman.

2.6 Graduate Entrepreneurship in Oman
Graduate engineering education has progressively prioritized the development of innovative capacities, highlighting the importance of technical expertise and creative and anticipatory skills that might foster entrepreneurship (Al-Baimani et al., 2021). In Oman, this emphasis corresponds with Vision 2040, which aims for knowledge-based economic development and encourages entrepreneurship to diversify the nation's historically oil-dependent economy (Ministry of Economy, 2019). In this context, engineering graduates are anticipated to address urgent industrial issues through creative problem-solving and strong prototyping abilities (Chryssou, 2020).

Recent work highlights Integrated Design Thinking (IDT) as a vital intermediary between graduates' perceived innovation competencies and their confidence in prototyping. Research indicates that only perceiving one's innovative skills is inadequate without an aligned attitude and approach to convert theoretical knowledge into practical results (Carlgren, Rauth, & Elmquist, 2016). Hypotheses assert that the self-perception of IDT mediates the relationship between (a) self-perception of innovation capabilities and self-reported confidence in prototyping (H8), (b) familiarity with engineering innovation tools and prototyping confidence (H9), and (c) systematic invention applications and prototyping confidence (H10). IDT enhances problem-solving skills and strengthens graduates' confidence in their prototype capabilities by integrating empathetic user research, iterative testing, and rapid prototyping methods (Cennamo & Kalk, 2019).

The government of Oman has implemented regulations and established organizations, such as the National Innovation Strategy, the Industrial Innovation Center, and the Oman Technology Fund, to facilitate the entrepreneurial endeavors of engineering graduates (Public Authority for SME Development, 2022). These initiatives enhance the curricular modifications implemented by the College of Engineering (CoE) at the National University of Science and Technology (NUST), directing capstone projects towards national goals and incorporating entrepreneurial elements. CoE programs enhance design thinking mindsets in engineering students by instructing them in the methodical application of systematic invention and acquainting them with innovation tools, resulting in increased self-efficacy in prototype projects.

Empirical research demonstrates that design thinking facilitates the transition from ideation to functional prototypes by elucidating user requirements, improving problem framing, and promoting iterative experimentation (Carlgren et al., 2016). Consequently, graduates with strong self-perceptions of IDT are more inclined to shift confidently from theoretical designs to prototypes, closing the gap between conceptual engineering solutions and market-ready goods (Al-Baimani et al., 2021). This synchronization of educational methodologies with national economic goals fortifies Oman's innovation ecosystem and equips engineering graduates to excel in a progressively knowledge-based economy.

Next, Section 3 presents this study's research methodology, design, and demographic data.

3. Research Methodology

3.1 Research Design

A structured questionnaire comprising five latent constructs and 19 items was created for the quantitative approach based on literature-derived variables (Appendix 1) to measure students' self-perception. The research proposal and the survey instrument went through ethics clearance from the National University of Science and Technology's Ethics and Biosafety Committee; the instrument was piloted among a small cohort of third-year engineering students. Subsequent refinements were made to ensure greater clarity before being disseminated to 326 engineering undergraduates in Years 3 and 4 since these formed the population of students who had completed the mandatory entrepreneurship course in Year 2. The final turnout yielded 200 responses. Data were then analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM), using SmartPLS 4 (Ringle et al., 2024), with bootstrapping employed to test the statistical significance of the hypothesized relationships. Tables and Figures (1-4) were drawn using SMART PLS4. Figure 5 was drawn using SMART Draw.

3.2 Development of the Survey Instrument

Drawing from the literature review, the constructs and variables for measuring the latent variables were identified for the Structured Equation Modeling. Appendix 1 presents the survey design.

3.3 Demographic Composition

The demographic composition was 98 percent Omani and two percent other nationalities. Gender distribution was 80.8 per cent female and 19.2 per cent male students from eight engineering programs: Mechanical and Industrial, Petroleum, Instrumentation, Civil, Electrical, Chemical, Biomedical, and Computer Engineering, Years 3 and 4 at the CoE, NUST, Oman.

3.4 Development of the Conceptual Models

Design thinking is a user-centric methodology for recognizing and addressing intricate problems, generally directed by empathy, problem identification, ideation, prototyping, and evaluation. Although these stages provide a systematic framework, they frequently intersect and recur, facilitating adaptability and ongoing enhancement. The suggested conceptual model incorporates TRIZ—a methodology aimed at identifying contradictions and generating imaginative solutions—into the design thinking phases to augment creativity and tackle real-world limitations. Commencing with stakeholder empathy, the process continues with formulating explicit problem statements and applying TRIZ concepts to facilitate ideation. This technology-oriented viewpoint endorses sustainable, human-centric solutions enhanced by iterative prototyping and risk evaluation. Subsequent feedback loops entail active testing with end-users, facilitating ongoing adaptation and enhancement. Integrating TRIZ insights with a comprehensive design thinking framework equips students and practitioners with powerful engineering tools and interdisciplinary cooperation abilities, promoting innovative product or service results. As depicted in **Figure 1**, this framework reflects the simultaneous interactions of linear and non-linear components, integrating TRIZ and technological features at each phase of Design Thinking (Hede et al., 2015). By highlighting the significance of human requirements, real-time testing, iterative development, prioritizing feasibility and sustainability, the integrated model can provide more comprehensive and realistic solutions (Micheli et al., 2019). This synergy offers a systematic, adaptable, solution-oriented methodology that drives innovative and lasting results.

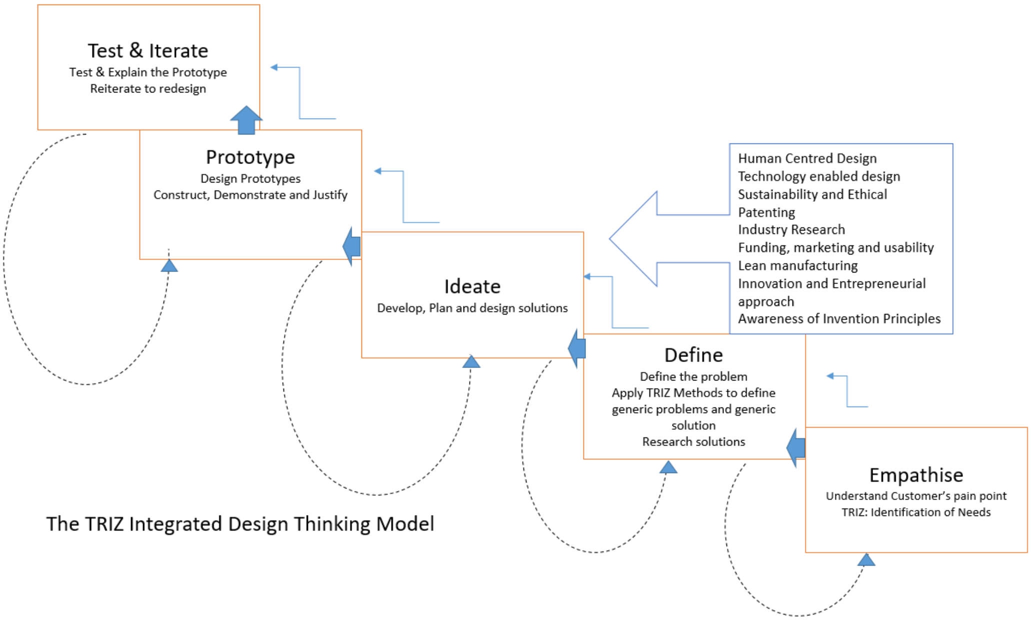

Figure 1: Technology & TRIZ Integrated DT Approach for engineering entrepreneurship (Authors' model)

Figure 2. presents the conceptual model used to test the variables drawn from the literature review. It highlights the influence of Innovation Capabilities, Systematic Invention processes, and Knowledge of Innovation Technologies on Prototyping capabilities, mediated by Technology and TRIZ-Integrated Design Thinking.

3.5 Research Hypotheses

The following hypotheses assume a theoretical chain in which engineering students' overall innovation capability, development of Systematic Invention (TRIZ included), and understanding of engineering innovation tools (both general and specialized, e.g. TRIZ) facilitate the adoption and effective use of a design thinking approach, resulting in the development of prototypes.

Direct Effects Hypotheses

H1: Self-perception of Innovation Capabilities positively influence the development of Self-perception of Integrated Design Thinking.
H2: Self-perception of Innovation Capabilities positively influences self-reported confidence in Prototyping.
H3: Self-perception of Integrated Design Thinking significantly influences self-reported confidence in Prototyping.
H4: Self-reported familiarity with Engineering Innovation Tools positively influences Self-Perception of Integrated Design Thinking.
H5: Self-reported familiarity with Engineering Innovation Tools positively influences self-reported confidence Prototyping.
H6: Self-reported application of Systematic Invention significantly influences Self-perception of Integrated Design Thinking.

H7: Self-reported application of Systematic Invention positively influences self-reported confidence in Prototyping.

Indirect Effects
H8: Self-perception of Integrated Design Thinking mediates the relationship between Self-perception of Innovation Capabilities and self-reported confidence in Prototyping.
H9: Self-perception of Integrated Design Thinking mediates the relationship between Self-reported familiarity with Engineering Innovation Tools and self-reported confidence in Prototyping.
H10: Self-perception of Integrated Design Thinking mediates the relationship between Self-reported application of Systematic Invention and self-reported confidence in Prototyping.

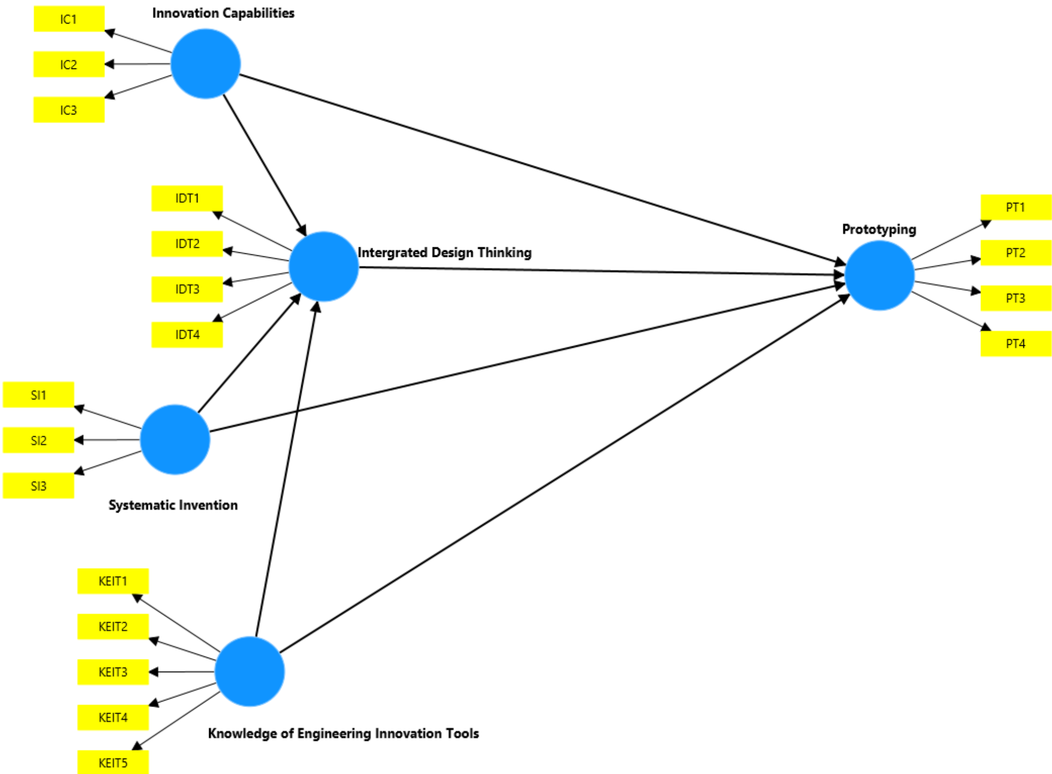

Figure 2: Conceptual Model: – Technology & TRIZ-based Integrated Design Thinking Model for engineering entrepreneurship in Oman (Authors' model)

4. Results and Analysis
Construct reliability and validity

The study of the measurement model reveals substantial reliability and validity across most constructs, establishing a solid basis for evaluating the structural model. **Table 1** shows the Construct reliability and validity.

Table 1: Construct Reliability and Validity

		Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
Innovation Capabilities		0.601	0.610	0.791	0.560
IC1	0.841				
IC2	0.664				
IC3	0.730				
Integrated Design Thinking		0.762	0.769	0.849	0.585
IDT1	0.768				
IDT2	0.694				
IDT3	0.826				
IDT4	0.765				
Knowledge of Engineering Innovation Tools		0.784	0.788	0.853	0.537
KEIT1	0.715				
KEIT2	0.687				
KEIT3	0.782				
KEIT4	0.729				
KEIT5	0.748				
Prototyping		0.762	0.767	0.849	0.585
PT1	0.765				
PT2	0.698				
PT3	0.823				
PT4	0.769				
Systematic Invention		0.732	0.759	0.847	0.650
SI1	0.797				
SI2	0.753				
SI3	0.864				

The Self-perception of Innovation Capabilities construct demonstrates moderate reliability, as shown by a Cronbach's alpha of 0.601, which falls below the 0.7 standard. Nonetheless, its composite reliability (0.791) and average variance extracted (AVE = 0.560) adhere to acceptable criteria, indicating adequate convergent validity. The indicator loadings for IC1 (0.841) are robust, but IC2 (0.664) and IC3 (0.730) exhibit moderate contributions. Additional constructs, such as Self-perception of Integrated Design Thinking, Self-perception of Knowledge of Engineering Innovation Tools, Self-perceived confidence in Prototyping, and implementation of Systematic Invention, satisfy or exceed the criteria for dependability and validity. Cronbach's alpha ratings span from 0.732

to 0.784, composite reliability values vary from 0.847 to 0.853, and AVE values surpass 0.5 for all constructs, signifying strong internal consistency and convergent validity. Indicator loadings for these constructs vary from mild to intense. None of the constructs exhibit any significant problems with reliability or convergent validity problems, affirming the measurement approach's robustness. Although Innovation Capabilities exhibits marginally lower internal consistency, its adequate convergent validity justifies its preservation. This validation supports advancing to the structural model analysis to examine hypothesized linkages, measure explanatory capacity, and evaluate the model's predictive significance.

Heterotrait-monotrait ratio (HTMT) – Matrix

The correlation matrix demonstrates that, with correlations ranging from 0.493 to 0.640, most concept associations fall below acceptable levels, confirming discriminant validity and controllable multicollinearity. **Table 2** presents the HTMT Matrix.

Table 2: Heterotrait-Monotrait Ratio (HTMT) - Matrix

	Innovation Capabilities	**Intergrated Design Thinking**	**Knowledge of Engineering Innovation Tools**	**Prototyping**
Innovation Capabilities				
Integrated Design Thinking	**0.513**			
Knowledge of Engineering Innovation Tools	**0.554**	**0.612**		
Prototyping	**0.513**	**1.312**	**0.612**	
Systematic Invention	**0.493**	**0.640**	**0.596**	**0.640**

The substantial correlation (1.312) between Prototyping and Integrated Design Thinking signifies severe multicollinearity or inadequate discriminant validity, indicating considerable conceptual or measurement overlap. This matter necessitates additional examination via tests such as HTMT or Fornell-Larcker, but other constructions exhibit adequate distinctiveness. It makes sense to move forward with structural model analysis, but for reliable and valid results, the interaction between prototyping and integrated design thinking must be improved and reevaluated.

The Model Fit summary

The model fit (**Table 3**) indices demonstrate a moderately acceptable fit, with an SRMR value of 0.098, slightly beyond the required threshold of 0.08, indicating minor fit issues. The d_ULS value of 1.835 signifies manageable structural differences, whereas other indices, including d_G, Chi-square, and NFI, are either absent or not interpretable in this context. Since PLS-SEM prioritizes predictive accuracy over perfect fit, the model is judged strong enough to move on to structural analysis, with consideration for possible improvements in the structural linkages.

Table 3: The Model Fit

	Saturated model	Estimated model
SRMR	0.098	0.098
d_ULS	1.835	1.835
d_G	n/a	n/a
Chi-square	∞	∞
NFI	n/a	n/a

Direct Effects

Figure 3 & **Table 4** presents the sample mean, standard deviation, T Statistics, P Values, and Variance Inflation Factor for hypothesis testing.

Table 4: Hypothesis Test for Direct Effects

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values	VIF
Innovation Capabilities -> Integrated Design Thinking	0.143	0.146	0.048	2.960	0.003	1.214
Innovation Capabilities -> Prototyping	0.142	0.145	0.048	2.941	0.003	1.245
Integrated Design Thinking -> Prototyping	1.001	1.001	0.001	1420.509	0.000	1.508
Knowledge of Engineering Innovation Tools -> Integrated Design Thinking	0.279	0.281	0.049	5.659	0.000	1.363
Knowledge of Engineering Innovation Tools -> Prototyping	0.280	0.281	0.049	5.663	0.000	1.480
Systematic Invention -> Integrated Design Thinking	0.313	0.314	0.046	6.807	0.000	1.314
Systematic Invention -> Prototyping	0.313	0.313	0.046	6.801	0.000	1.462

H1: Self-perception of Innovation Capabilities → Self-perception of Integrated Design Thinking

The path coefficient (O = 0.143) is positive and statistically significant (p = 0.003, T = 2.960), with a Variance Inflation Factor (VIF) of 1.214, signifying no multicollinearity concerns. This study corroborates the premise that Innovation Capabilities exert a favorable impact on Integrated Design Thinking. The outcome highlights the significance of innovation capabilities in improving design thinking processes within the innovation framework.

H2: Self-perception of Innovation Capabilities → Self-perception of Prototyping Skills

The association is statistically significant (O = 0.142, p = 0.003, T = 2.941), with a Variance Inflation Factor (VIF) of 1.245, suggesting no multicollinearity issues. This research corroborates the concept that Innovation Capabilities positively affect Prototyping, indicating that strong innovation capabilities directly enhance the development and refining of prototypes.

H3: Self-perception of Integrated Design Thinking → Self-perception of Prototyping Skills

This path coefficient exhibits a remarkably robust impact (O = 1.001, p = 0.000, T = 1420.509), accompanied by a VIF of 1.508. The almost perfect coefficient signifies a high correlation, prompting inquiries about possible duplication or conceptual overlap between the two conceptions. Nevertheless, the proposition that Integrated Design Thinking substantially impacts Prototyping is well-supported.

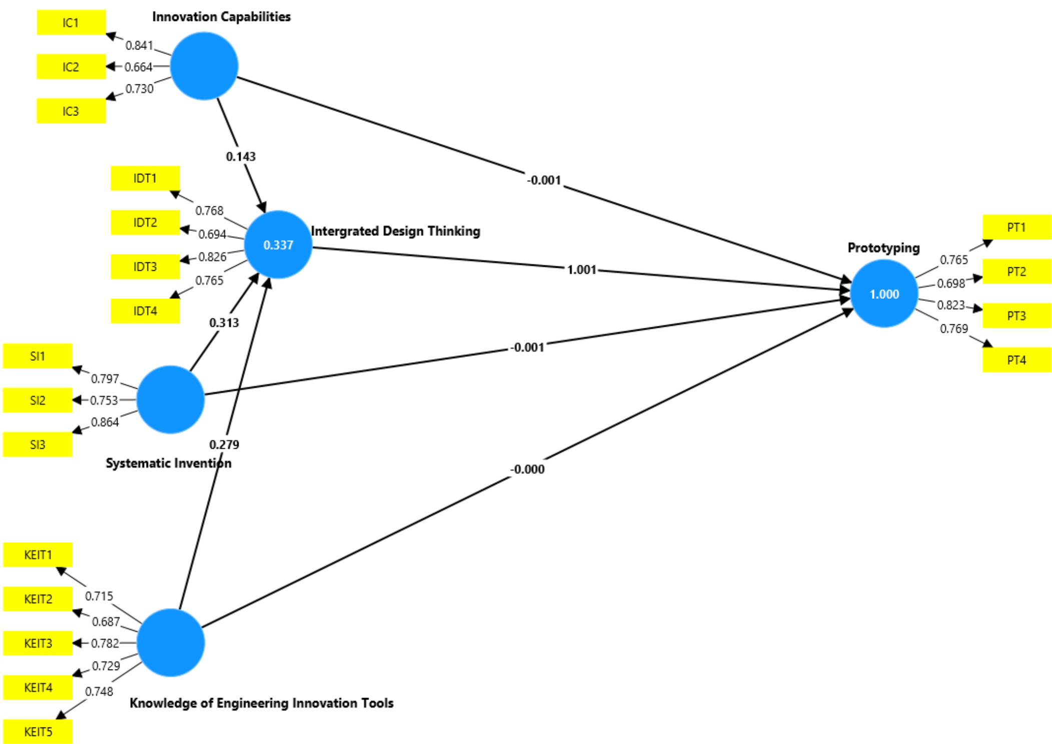

Figure 3: Conceptual Model – Path Coefficient & Direct Effect (Authors' model)

H4: Self-reported familiarity with Engineering Innovation Tools → Self-perception of Integrated Design Thinking

The path coefficient (O = 0.143) is positive and statistically significant (p = 0.003, T = 2.960), with a Variance Inflation Factor (VIF) value of 1.214, indicating the absence of multicollinearity issues. This finding supports the hypothesis that Innovation Capabilities positively influence Integrated Design Thinking. The result highlights the importance of innovation capabilities in enhancing design thinking processes within the innovation framework.

H5: Self-reported familiarity with Engineering Innovation Tools → Self-perception of Prototyping Skills

The association exhibits statistical significance (O = 0.280, p = 0.000, T = 5.663), with a Variance Inflation Factor (VIF) 1.480. This research corroborates the premise that familiarity with Engineering Innovation Tools favorably impacts Prototyping, suggesting that engineering tools are essential for the effective production of prototypes.

H6: Self- Reported confidence in the application of Systematic Invention → Self-perception of Integrated Design Thinking

The path coefficient (O = 0.313) is statistically significant (p = 0.000, T = 6.807), with a Variance Inflation Factor (VIF) of 1.314, signifying no multicollinearity concerns. This discovery corroborates that Systematic Invention substantially impacts Integrated Design Thinking, highlighting its role in structured and effective design innovation.

H7: Self- Reported confidence in the application of Systematic Invention → Self Perception of Prototyping

The association exhibits statistical significance (O = 0.313, p = 0.000, T = 6.801) and a Variance Inflation Factor (VIF) of 1.462. This research corroborates that Systematic Invention favorably impacts Prototyping, highlighting its function in systematically enhancing inventive prototypes.

Specific indirect effects

Figure 4 and Table 5 illustrate the indirect effects and relationship between Integrated Design Thinking, Systematic Invention, Innovation Capabilities and Prototyping

Table 5: Hypothesis Test for Indirect Effects

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
Innovation Capabilities -> Integrated Design Thinking -> Prototyping	0.143	0.146	0.048	2.959	0.003
Knowledge of Engineering Innovation Tools -> Integrated Design Thinking -> Prototyping	0.280	0.281	0.049	5.660	0.000
Systematic Invention -> Integrated Design Thinking -> Prototyping	0.314	0.314	0.046	6.802	0.000

H8: Innovation Capabilities Leading to Integrated Design Thinking and Prototyping

The indirect effect (O = 0.143, p = 0.003, T = 2.959) is statistically significant, indicating that Integrated Design Thinking mediates between Innovation Capabilities and Prototyping. This finding indicates that innovation capabilities play a role in prototype development by influencing integrated design thinking processes, emphasizing the importance of employing design thinking to improve prototyping.

H9: Understanding of Engineering Innovation Tools → Integrated Design Thinking → Prototype Development
The indirect effect (O = 0.280, p = 0.000, T = 5.660) is statistically significant, suggesting that Integrated Design Thinking is a strong mediator in the relationship between Knowledge of Engineering Innovation Tools and Prototyping. This finding indicates that effective use of engineering innovation tools improves design thinking processes, thereby significantly aiding the development and refinement of prototypes.

H10: Systematic Invention leads to Integrated Design Thinking, culminating in Prototyping.
The indirect effect (O = 0.314, p = 0.000, T = 6.802) is statistically significant, indicating that Integrated Design Thinking mediates between Systematic Invention and Prototyping. This finding demonstrates that systematic invention improves the structured application of design thinking, essential for enhancing prototyping outcomes.

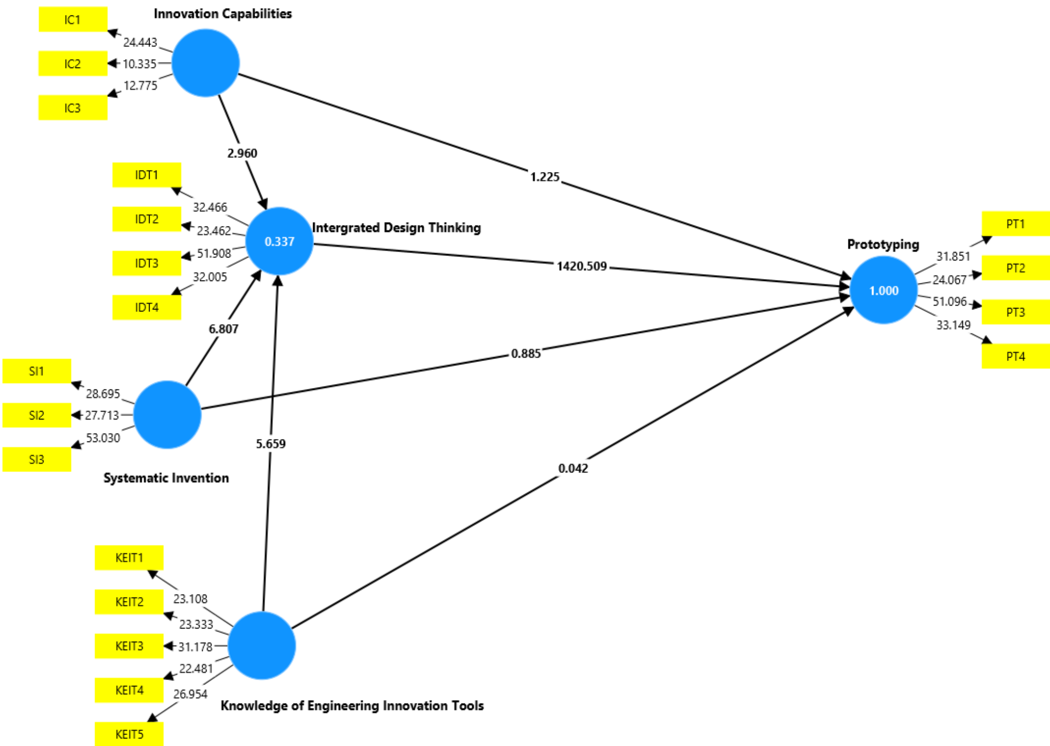

Figure 4: Conceptual Model – Path Coefficient & Indirect Effect (Authors' model)

5. Discussion and Recommendations

5.1 Discussion

This study investigated the incorporation of technology and TRIZ-augmented design thinking skills in equipping engineering graduates for innovation and entrepreneurship. Three primary constructs—self-assessment of Innovation Capabilities, self-reported familiarity with Engineering Innovation Tools, and confidence in the application of Systematic Invention—were examined for their impact on self-assessment of Integrated Design Thinking and self-reported confidence in Prototyping. The primary emphasis was on the mediating function of Integrated Design Thinking in converting students' creative and technical skills into concrete prototypes.

The Impact of Self-Perception on Design Thinking and Prototyping

The findings indicate that self-assessed Innovation Capabilities significantly influence self-perception of Integrated Design Thinking (H1) and self-reported confidence in Prototyping (H2). Students who perceive themselves as proficient innovators exhibiting abilities such as identifying innovative ideas, managing creative risks, and adjusting to new technologies are better prepared to participate in iterative, user-centered design processes. This enhanced self-perception correlates with increased self-reported prototyping outcomes, as students exhibit greater confidence in swiftly developing, testing, and refining their ideas.

Moreover, self-assessment of Integrated Design Thinking was shown as a strong predictor of self-reported confidence in Prototyping (H3). This almost optimal path coefficient emphasizes the importance of empathic, iterative, and user-centric methodologies in design thinking for developing technologically sound and market-ready prototypes. The relationship between students' perceptions of their design thinking abilities and their self-reported skills in transforming concepts into working prototypes indicates that structured design training is essential for cultivating future engineering innovators.

The Importance of Familiarity with Innovation Tools and Systematic Invention

Self-reported familiarity with Engineering Innovation Tools proved to be a crucial determinant of self-assessment in Integrated Design Thinking (H4) and self-reported confidence in Prototyping (H5). Tools like CAD software, simulation platforms, and TRIZ-based applications connect concept development with empirical testing. When students acknowledge their proficiency with these tools, they experience accelerated iteration cycles and more substantive assessments of design concepts, resulting in superior prototypes.

Similarly, self-reported utilization of Systematic Invention (primarily via TRIZ) markedly affects self-assessment of Integrated Design Thinking (H6) and self-reported assurance in Prototyping (H7). Systematic Invention techniques encourage students to systematically find and examine inconsistencies in engineering problems, prompting them to develop innovative solutions. By consciously utilizing systematic invention methods, students enhance their design thinking skills by refining ideas from multiple perspectives and reporting greater assurance in translating their solutions into prototypes.

Mediating Role of Integrated Design Thinking

The significance of Integrated Design Thinking as an intermediary between (a) self-assessed innovation competencies, engineering innovation instruments, and systematic invention, and (b) prototyping, is substantiated by the indirect pathways (H8, H9). The findings emphasize that, despite students having innovative inclinations or familiarity with engineering tools, these advantages may be inadequately leveraged for prototyping unless situated inside a cohesive, human-centered design thinking framework. This highlights the necessity for engineering educators to integrate TRIZ-based systematic Invention Principles and technological tool utilization into holistic design-thinking curriculum, rather than presenting them as isolated courses.

Implications for Teaching, Assessment, and Curriculum Design

The outcomes are consistent with prior research advocating interdisciplinary, holistic, and guided experiences in problem-solving and simulation (Martorelli and Gloria, 2023; Sheng, 2023; Carvalho Botega and da Silva, 2022; Qiu et al., 2022; Wang et al., 2022; Cano-Moreno et al., 2021; Belski, 2019). An educational approach that merges TRIZ, design thinking, and technological tools can help students develop an entrepreneurial mindset, backed by strong self-perception of design and prototyping skills. Activities such as hackathons, incubator programs, and collaborative design projects enable students to practice disciplined creativity and engineering problem-solving in real-world contexts. Regular prototyping, framed within iterative feedback loops, sharpens their adaptability, teamwork, and market awareness attributes that position engineering graduates for success in today's innovation-driven sectors.

Despite these promising insights, discussions with engineering faculty reveal a persistent challenge of GPA-focused mindsets among students and employers. Memorizing or regurgitating theory in exams may yield high GPAs yet fail to measure genuine engineering problem-solving aptitude, especially the ability to integrate the right tool or technology to achieve innovative outcomes. While some students excel through creative projects, such cases remain exceptions rather than the norm. Given Oman's Ministry of Higher Education, Research and Innovation directive to strengthen innovation capabilities, engineering programs must critically re-examine outcomes-based teaching and assessment strategies. Moving beyond traditional exam models is crucial: authentic assessments should capture students' self-perceived and demonstrated abilities to design, prototype, and systematically refine engineering solutions across courses, not solely in capstone projects or lab exercises.

Empowering Female Engineering Graduates Through TRIZ-Integrated Design Thinking

The College of Engineering (CoE) has a significant population of female students whose employment opportunities and societal constraints can limit them from traditional engineering roles. Curriculum design, pedagogy, and assessments must, therefore, reinforce how engineering graduates, particularly Omani female engineers can forge entrepreneurial careers by leveraging TRIZ-Integrated Design Thinking. Through initiatives emphasising self-perception of core skills and systematic use of engineering innovation tools, female graduates gain tangible pathways for innovation-led economic contributions.

The study indicates a strong correlation between self-assessed innovation skills, self-reported familiarity with engineering tools, and methodical invention methodologies and the success of integrated design thinking and prototyping. By examining learners' perceptions of their innovative abilities and implementing genuine, practical assessments of design projects, engineering educators can methodically cultivate the forthcoming generation of innovators, especially women prepared for leadership in Oman's developing, innovation-driven economy.

Recommendation and the Proposed Framework

Drawing from survey findings, we propose an integrated framework (illustrated in **Figure 5**) that situates TRIZ, design thinking, and technology tools at the heart of a continuous cycle of self-assessment, prototyping, and user feedback. Such a model enhances learning outcomes and student self-confidence and emphasizes aligning students' innovation capabilities with practical, market-oriented results.

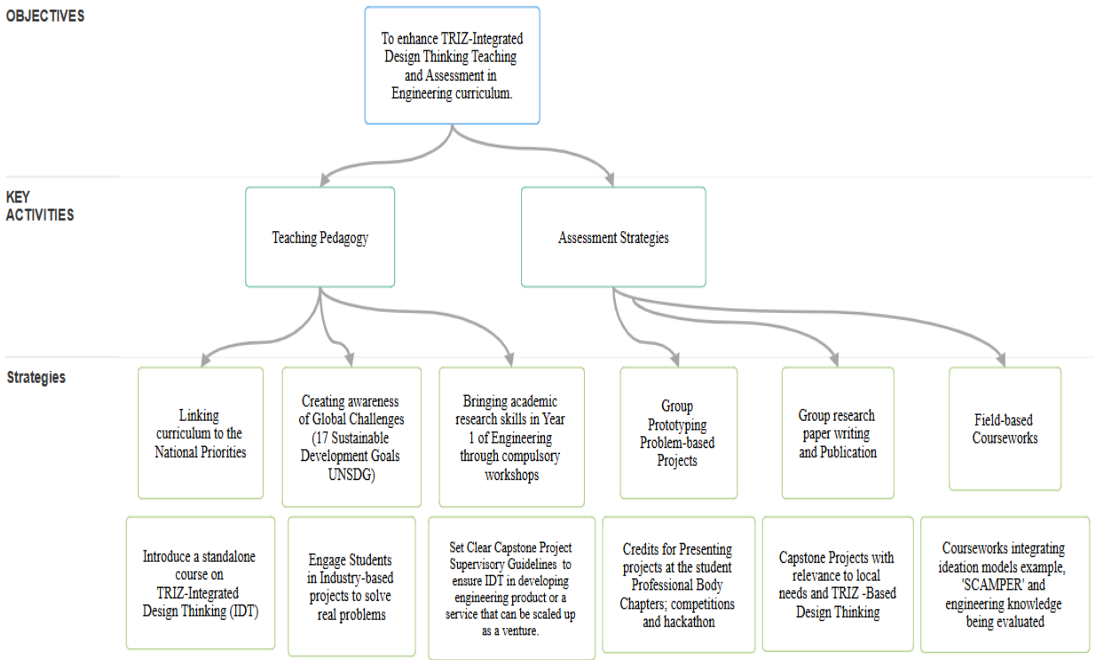

Figure 5 T&L Framework: TRIZ Integration Strategies in Engineering Teaching and Assessment (Authors' own)

5.2 Limitations and Future Research

Although this work offers substantial empirical evidence to support the suggested paradigm, many limitations must also be recognized. The notably high correlation between self-perceived Integrated Design Thinking and Prototyping may suggest overlapping conceptions or measurement concerns that require further examination in subsequent studies. Secondly, the study may be limited by sample characteristics (e.g. a singular institution or location), which may restrict the generalizability of the results. It would be helpful for future research to incorporate longitudinal designs that examine the evolution of these competencies over time and their correlation with tangible entrepreneurial success following graduation. Qualitative insights may enhance quantitative findings by investigating how students and instructors perceive the interaction of these constructs in practice.

6. Conclusion

The integration of TRIZ-enhanced design thinking into engineering education is pivotal in cultivating self-aware, innovative engineers in Oman. By emphasizing self-perception and self-reporting of key competencies—namely design thinking, familiarity with innovation tools, and systematic invention—educational institutions can foster a deeper confidence in problem-solving and prototyping abilities. This self-assessment framework enables students to recognize their strengths and identify areas for growth, ensuring that they are not only technically proficient but also adept at transforming creative concepts into tangible, market-ready solutions.

Such an approach aligns with Oman's broader goal of diversifying its economy and building a knowledge-based society driven by entrepreneurial innovation. As students gain greater self-awareness of their capabilities, they are empowered to tackle real-world challenges through empathetic design, iterative prototyping, and strategic use of technology. The TRIZ-Integrated Design Thinking Model, therefore, equips future engineers to become leaders who can navigate and shape a dynamic global market.

By creating an environment that prioritizes exploration, iteration, and collaborative learning, Oman's engineering education can bridge the gap between traditional theoretical instruction and the practical demands of a technology-driven future. This comprehensive educational strategy not only enhances technical and creative skills but also nurtures visionary entrepreneurs, positioning Oman at the forefront of innovation and long-term economic growth.

Appendices

Appendix 1: Survey Constructs and Coding

Funding details:

The Author and the Co-authors are grateful to the National University of Science & Technology, Oman, for supporting the National University Faculty Research Grant NUFRG16-2022-2024.

Disclosure statement:

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethics approval:

The authors thank the NU Ethics and Bio-Safety Committee for approving data collection from the College of Engineering, Oman, under NUFRG16 2022-2024.

Data set availability:

The author confirms that all data generated or analysed during this study are included in this published article. Raw data can be made available on request.

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Appendix 1

Latent Variables	Observed Variable	Survey Constructs/Items	Code
Self-Perception of Integrated Design Thinking Measures a respondent's *self-reported* use of structured, methodical processes (e.g., planning, TRIZ) when designing or inventing solutions. These items tap into the *design thinking mindset*: empathy, creative ideation, and iterative processes. Martorelli and Gloria (2023), Sheng, 2023; Dodun et al. (2022), Qiu et al. (2022),Cano-Moreno et al., 2021;Da Silva et al., 2020; Belski, 2019; Lee, 2018; Chang et al.,2016 and Mawale et al.,(2016)	Empathise & Define	I understand the importance of empathizing with users to identify their needs.	IDT 1
	Ideate	I feel comfortable challenging conventional solutions during ideation sessions	IDT2
	Prototype	I can develop functional prototypes to test potential solutions.	IDT3
	Test and Reiterate	I actively refine prototypes based on testing outcomes and feedback.	IDT4
Self-Reported Prototyping Competencies Captures a respondent's *self-reported* comfort, skills, and actual practice of prototyping (e.g., creating low-fidelity prototypes, iterating on user feedback). These items measure self-perceived prototyping behaviors and skills. Deininger, M., Daly, S. R., Sienko, K. H., & Lee, J. C. (2017). Novice designers' use of prototypes in engineering design. *Design studies*, *51*, 25-65.		I am familiar with creating low-fidelity prototypes (e.g., sketches, mockups).	PT1
		I can develop functional prototypes to test potential solutions.	PT2
		I actively refine prototypes based on testing outcomes and feedback.	PT3
		I understand the role of rapid prototyping in iterative design processes.	PT4

Self-Perceived confidence in Innovation Capabilities (IC) Reflects a respondent's *confidence* in generating novel, impactful solutions and integrating diverse elements of innovation (e.g., empathy, ideation, feedback). These items capture confidence in one's overall innovative capacity and mindset. Jørgensen, F., & Busk Kofoed, L. (2007)	Creative Problem-Solving and Ideation Jørgensen & Busk (2007)	I feel confident in applying Design Thinking strategies to develop innovative solutions.	IC1
	Value Creation (Ibid)	I am capable of creating impactful and novel designs that address real-world problems.	IC2
	Knowledge Integration (Ibid)	I am skilled at integrating empathy, ideation, prototyping, and feedback to innovate effectively.	IC3
Self-Reported application of Systematic Invention (SI) Measures a respondent's *self-reported* use of structured, methodical processes (e.g., planning, TRIZ) when designing or inventing solutions. These items measure whether respondents perceive themselves as using methodical, structured approaches. Barak & Goffer (2002)	Methodical Process Barak & Goffer (2002)	I follow systematic processes to develop and test new inventions.	SI1
	Iterative Learning: Barak & Goffer (2002)	I utilize structured methodologies like TRIZ (Theory of Inventive Problem Solving) to approach design challenges.	SI2
	Evaluation and Selection Lichtenthaler, U. (2020)	My invention process includes thorough planning and detailed execution.	SI3
Self-Reported familiarity with Knowledge of Engineering Innovation Tools (KEIT) Captures a respondent's *self-reported* familiarity, hands-on experience, or comfort using engineering tools (e.g., TRIZ, simulation software, 3D printing, etc.). These items focus on familiarity and usage of engineering tools essential for innovation.	Technology Integration	I can integrate Virtual Reality Technology into engineering design and simulation processes.	KEIT1
		I understand how to preprocess data for Machine Learning applications.	KEIT2
		I have utilized simulation software (e.g., MATLAB, ANSYS, Simulink, CAD) in my studies.	KEIT3
		I have hands-on experience with 3D printing technologies for prototyping.	KEIT4
		I have applied TRIZ methodologies to solve engineering problems.	KEIT5

Martorelli and Gloria (2023), Sheng, 2023; Dodun et al. (2022), Qiu et al. (2022),Cano-Moreno et al., 2021;Da Silva et al., 2020; Belski, 2019; Lee, 2018; Chang et al.,2016 and Mawale et al.,(2016)			